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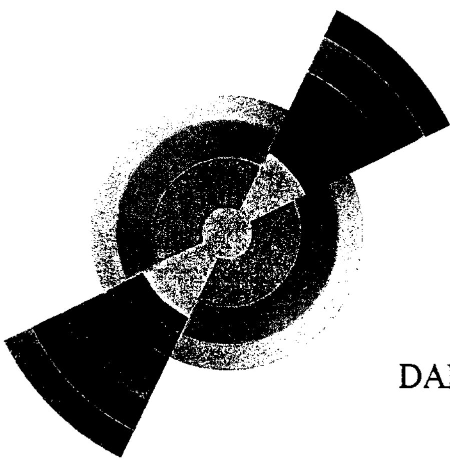

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LOW-ENERGY K$^-$ - PROTON INTERACTIONS

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Abstract

A general coupled-channel formalism using a particle basis is presented, and applied succesfully to all the low energy $K^- - p$ process except the *1s* atomic level shift. The effect of the initial state interactions on the $K^- - p$ radiative capture branching ratios are found to be quite sizable.

1 Introduction

The interest in the K^--proton interactions is multifold[1], mainly due to two facts.

i) The $\Lambda(1405)$ resonance lies just below the $K^- - p$ threshold at 1432 MeV and offers an appropriate means to study the nature of this resonance. In the literature the $\Lambda(1405)$ is considered as an *s*-channel resonance [2] or as a quasi-bound $(K^- - N, \Sigma\pi)$ state [3]. In the quark-model approaches, this hyperon is considered as a pure q^3 state [4], a quasi-bound $\overline{K}$N state [5] or still as a hybrid $(q^3+q^4\overline{q}...)$ state [6]. A number of potential model fits to the scattering data incorporate the $\Lambda(1405)$ as a quasi-bound $(K - N, \Sigma\pi)$ resonance [7-10]. Very recent approaches treat this hyperon as an "elementary" field [11] or as a quasi-bound state [12] using chiral perturbation theory, or consider it as composed by an SU(2) soliton and a kaon bound in a S-wave [13].

ii) Even at low energies the K^- can scatter off the proton not only elastically but also go through inelastic reactions.

Investigating the K^--proton system, implies hence studying *simultaneously* the following eight channels:

$K^- \; p \to K^- \; p \; , \overline{K^0} - n \; , \Sigma^+\pi^- \; , \Sigma^0\pi^0 \; , \Sigma^-\pi^+ \; , \Lambda\pi^0 \; , \Lambda \; \gamma \; , \Sigma \; \gamma.$

Besides, the amplitudes of the two radiative capture reactions can be related, *via* the crossing symmetry, to those of the strangeness photoproduction $\gamma p \to K^+\Lambda(K^+\Sigma^0)$. Much effort has been done experimentally and theoretically to understand this system. Close to the threshold (*i.e.* $p_K \leq 200 MeV/c$), there are roughly 70 total cross section data points [14]for the six strong interaction scattering process. In addition, threshold branching ratios have been measured with high accuracy: [15, 16]:

$$\gamma = \Gamma(K^-p \to \pi^+\Sigma^-)/\Gamma(K^-p \to \pi^-\Sigma^+) = 2.36 \pm .04,$$

$$R_c = \Gamma(K^-p \to \mathit{charged\ particles})/\Gamma(K^-p \to \mathit{all}) = .664 \pm .011,$$

$$R_n = \Gamma(K^-p \to \pi^0\Lambda)/\Gamma(K^-p \to \ \mathit{all\ neutral\ states}) = .189 \pm .015,$$

$$R_{\Lambda\gamma} = \Gamma(K^-p \to \Lambda\gamma)/\Gamma(K^-p \to \mathit{all}) = .86 \pm .07 \pm .09 \times 10^{-3} \ ,$$

$$R_{\Sigma\gamma} = \Gamma(K^-p \to \Sigma^0\gamma)/\Gamma(K^-p \to \mathit{all}) = 1.44 \pm .20 \pm .11 \times 10^{-3}.$$

Hence the existing data put tight constraints on the threshold amplitudes and potential coupling strengths. However, at present there is no comprehensive analysis which includes *both* the hadronic and electromagnetic branching ratios of the K^-p system.

In this contribution, we investigate all the low energy data within a *single model* using known coupling strengths and minimal SU(3) symmetry breaking for relevant vertices in the electromagnetic channels and emphasize the importance of the initial state interactions on the radiative capture branching ratios.

2 General Formalism

To study a coupled-channel system consisting of n hadronic channels and one electromagnetic channel, we assume that the interaction between channels can be represented for each partial wave l by real potentials of the form $V^l_{ij}(\sqrt{s}, k_i, k_j)$ with $\sqrt{s}$

the total energy and k_i the momentum of channel i in the center-of-mass frame. We also assume that the transition matrix element for each partial wave from channel i to channel j can be derived from a coupled-channel Lippmann-Schwinger equation:

$$T_{ij}(\sqrt{s}, k_i, k_j) = V_{ij}(\sqrt{s}, k_i, k_j) + \sum_m \int V_{im}(\sqrt{s}, k_i, q) G_m(\sqrt{s}, q) T_{mj}(\sqrt{s}, q, k_j) q^2 dq,$$

where $G_i(\sqrt{s}, q)$ is the propagator for channel i. The index l is suppressed since we are dealing only with the $l = 0$ partial wave.
Neglecting the back coupling of the photon channels, due to the weakness of the electromagnetic couplings, the T-matrix for radiative capture is the same as above with j replaced by γ and $m \neq \gamma$.
Since $\sqrt{s}$ and k_γ are fixed in the integral, we obtain for the T-matrix [10]:

$$T_{i\gamma}(\sqrt{(s)}, k_i, k_\gamma) = \sum_{m \neq \gamma} M_{im}(\sqrt{s}) V_{m\gamma}(\sqrt{s}, k_m, k_\gamma),$$

with the matrix M_{im} defined as

$$M_{im} \equiv \delta_{im} + \int V_{i,m}(\sqrt{s}, k_i, q) G_m(\sqrt{s}, q) v_{m\gamma}(q) q^2 dq + \sum_{n \neq \gamma} \int \int V_{in}(\sqrt{s}, k_i, q') \times$$
$$G_n(\sqrt{s}, q') V_{nm}(\sqrt{s}, q', q) G_m(\sqrt{s}, q) v_{m\gamma}(q) q'^2 dq' q^2 dq + \cdots .$$

The state m is the last hadronic one before the photon is produced. Since all the on-shell momenta are determined from $\sqrt{s}$ we have

$$T_{i\gamma}(\sqrt{s}) = \sum_{m \neq \gamma} M_{im}(\sqrt{s}) V_{m\gamma}(\sqrt{s}).$$

This convenient form for the transition matrix to the photon channels, separates out the strong part from the electromagnetic part of the interaction. The matrix M is determined entirely from the hadronic interactions. In the absence of channel-coupling M is the unit matrix. *Any deviation from unity is related to the initial state interactions.* For the strong channels we use separable potentials:

$$V^I_{ij}(k, k') = (g^2/4\pi) C^I_{ij} b^I_{ij} v_i(k) v_j(k'),$$

where the C^I_{ij} are determined from $SU(3)$-symmetry. The b^I_{ij} are "breaking parameters" which are allowed to vary from unity by $\pm 50\%$. The $v_i(k)$ are form factors, taken here to be equal to $\alpha_i^2/(\alpha_i^2+k^2)$ as well as for the hadronic vertex (*i.e.* half off-shell part) of the electromagnetic amplitude, and g is an overall strength constant. These potentials are used in a coupled-channel Lippmann-Schwinger equation with a non-relativistic propagator.

For the radiative capture channels, we can write:

$$F_{K^-p\to\Lambda\gamma(\Sigma^0\gamma)} = \sum A_m(\sqrt{s}) f_{m\to\Lambda\gamma(\Sigma^0\gamma)},$$

where the f_m's are the amplitudes to go from the hadronic channel m to the appropriate photon channel. These amplitudes are derivable from Feynman diagrams representing the leading order contributions to the photoproduction process and include "extended Born" terms: the Λ and the Σ^0 exchange , and the vector meson exchange terms (K^*, ρ). The quantities A_m are unitless complex numbers, and contain all the information about the initial state interactions for radiative capture. Generally the sum over m is restricted to states which have charged hadrons. For the $K^- - p$ process the problem is greatly simplified, since there are only 3 channels which have charged hadrons: $\pi^+\Sigma^-$, $\pi^-\Sigma^+$ and K^-p. To a very good approximation, the A_m's are the same for both the $\Lambda\gamma$ and the $\Sigma^0\gamma$ channels.

3 Results and Discussion

Using the above formalism, two different separable potentials were considered: one guided by $SU(3)$ for the relative channel couplings [10] which fits all the low energy data [13-15] except the *1s* atomic-level shift [17], and one from Ref. [9] which fits all the low energy data including the scattering length from the *1s* atomic-level shift. Values for the A_m at the K^-p threshold for each fit are given in Table 1.

The resonance at an energy of 1405 MeV was also fitted and produced [10] as a $K - N(\Sigma\pi)$ bound state resonance.

To get an acceptable fit to all the data and determine the range of the A_m, we let the b_{ij}^I vary from 0.5 to 1.5. The A_i are a measure of how much the initial state interactions enhance the single scattering amplitude. As mentionned above, in the K^-p radiative decay calculation, only A_1, A_3, and A_5 contribute: $F_{K^-p\to\Lambda\gamma} = A_1 f_{\Sigma^-\pi^+\to\Lambda\gamma} + A_3 f_{\Sigma^+\pi^-\to\Lambda\gamma} + A_5 f_{K^-p\to\Lambda\gamma}$. In the absence of initial state interactions, $A_1 = A_3 = 0$ and $A_5 = 1$. As can be seen in Table I, the magnitude of A_1, A_3, and A_5 are between 0.8 and 1.3. Hence , cancellations amoung the various amplitudes can make the radiative capture probability very sensitive to the initial state interactions.

Table 1: The A_i values for two different strong potentials.

A_i	Potential with $SU(3)$-Symmetry [10]	Tanaka & Suzuki Potential [9]
A_1	+ 1.20 + 0.52 i	+ 1.49 − 0.28 i
A_2	− 1.02 − 0.14 i	− 1.10 + 0.52 i
A_3	+ 0.83 − 0.23 i	+ 0.71 − 0.75 i
A_4	− 0.16 − 0.34 i	− 0.30 − 0.39 i
A_5	− 0.15 + 1.06 i	+ 2.01 + 2.55 i
A_6	+ 1.18 − 0.41 i	+ 2.08 − 1.12 i

The important problem of include the appropriate isospin breaking effects due to the mass differences of the particles was handeled by using the correct relativistic momenta and reduced energies in the propagator. The effects are very important in calculating the threshold branching ratios, where the Coulomb potential can be neglected [18] when calculating the branching ratios.

To calculate the observables, we need to determine the values of the free parameters by least-squares fitting procedure to the data. The search was done using MINUIT code [19] on 13 parameters: the three ranges for the strong channels, the six breaking factors for the strong channels b^I_{ij}, and the four strong vertex coupling constants $g_{Kp\Lambda}$, $g_{Kp\Sigma}$, $g_{\pi\Sigma\Sigma}$, and $g_{\pi\Sigma\Lambda}$. We allowed the b^I_{ij} to vary $\pm 50\%$ from unity. Three of the 4 coupling constants, $g_{Kp\Sigma}$, $g_{\pi\Sigma\Sigma}$, and $g_{\pi\Sigma\Lambda}$ varied by $\pm 50\%$, and the $g_{Kp\Lambda}$ coupling by $\pm 20\%$ from their SU(3) values respectively. Finally, The range parameters α were allowed to vary from 200 to 1000 MeV/c.

Our best fit values for the best known coupling constants are $g_{KN\Lambda}/\sqrt{4\pi} = -3.0$, and $g_{KN\Sigma}/\sqrt{4\pi} = 1.6$. Notice that their extracted values are in agreement with those obtained from strangeness photoproduction [20, 21] and hadronic sector [22, 23] analyses. The reduced χ^2 is 1.78.

3.1 Cross sections

In Fig. 1, we plot the total cross-section as a function kaon laboratory momentum P_{Lab}. The curves for each ratio correspond to the maximum allowed SU(3)-symmetry breaking as given above. The existing strong channels data are well reproduced. We have also studied in more details other breaking percentages and find [10] little sensitivity to the SU(3)-symmetry breaking effects in the domains studied here. Predictions for the two electromagnetic channels are also reported.

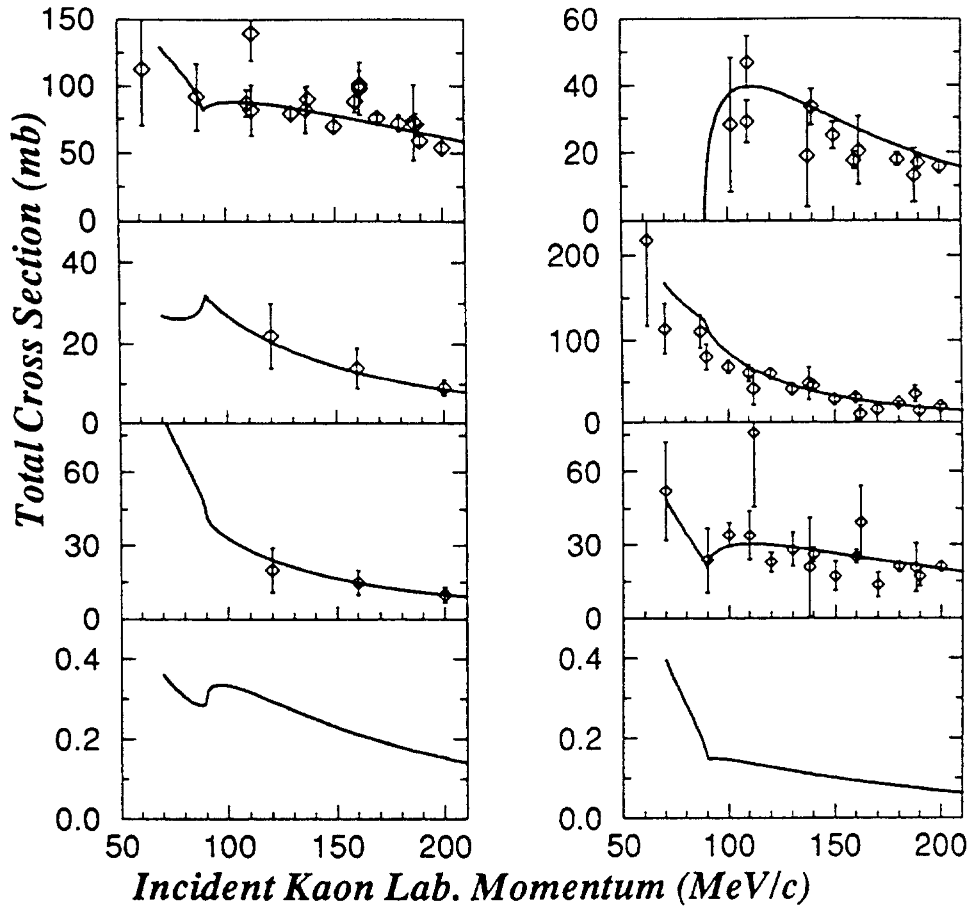

Figure 1: Total cross sections as a function of incident kaon momentum are compared with the available experimental data [14] for the six strong channels and the two electromagnetic channels: *a)* K^-p elastic scattering, *b)* $K^-p \to \overline{K^0}n$, *c)* $K^-p \to \pi^0\Lambda$, *d)* $K^-p \to \pi^+\Sigma^-$, *e)* $K^-p \to \pi^0\Sigma^0$, *f)* $K^-p \to \pi^-\Sigma^+$, *g)* $K^-p \to \Lambda\gamma$, and *h)* $K^-p \to \Sigma^0\gamma$.

3.2 Branching ratios

Tables 2 and 3 summarize threshold strong and electromagnetic branching ratios, respectively. Results of our calculation are in reasonable agreement with the data. The electromagnetic branching ratios deserve some comments.

The most striking feature comes from the drastical dependence of these branching ratios on the initial state interactions. The second row in Table 3 shows that if these interactions are switched off, the ratios $R_{\Lambda\gamma}$ and $R_{\Sigma\gamma}$ decrease by roughly a factor of 2 and more than one order of magnitude, respectively.

It is also interesting that at threshold $R_{\Lambda\gamma}$ is substantially less than $R_{\Sigma\gamma}$. Our recent

Table 2: K^-p threshold strong branching ratios

	γ	R_c	R_n
Present work	2.31	.661	.164
EXPERIMENT [15]	2.36 ± .04	.664 ± .011	.189 ± .015

Table 3: K^-p threshold radiative capture branching ratios. The final state interactions in the Tanaka & Suzuki Potential were included in this work.

Authors [Ref.]	$R_{\Lambda\gamma} \times 10^3$	$R_{\Sigma\gamma} \times 10^3$	Formalism
Present work	1.09	1.55	*coupled-channel* with FSI
Present work	0.56	0.12	*coupled-channel* without FSI
Zhong et al.[5]	1.90	2.30	*coupled-channel* with FSI
Tanaka & Suzuki[9]	17.5	3.29	*coupled-channel* with FSI
Workman & Fearing[24]	3.09	3.72	*Diagrammatic technique*
Williams et al.[25]	0.89	1.46	*Diagrammatic technique*
David et al.[21]	0.95	1.44	*Diagrammatic technique*
EXPERIMENT [16]	.86 ± .12	1.44 ± .20	

investigation [10] shows that this trend is general at energies below the $\overline{K^0}n$ threshold, while at higher energies the ratio $R_{\Lambda\gamma}$ becomes greater than $R_{\Sigma\gamma}$. Experimental data of these branching ratios at low energies with kaons in flight would help clarify the nature of the $\Lambda(1405)$.

The coupled channel calculation results by Zhong et al. [5] are too high roughly by a factor of 2, and our results using the Tanaka-Suzuki potential miss by far the data. Another approach, based on diagrammatic technique, has also been applied to this field. Williams et al. [25] obtain good agreement with the data, but their coupling constants disagree with the SU(3)-symmetry constraints. Workman-Fearing [24] and David et al. [21] respect the SU(3) values, and only the latter work produces results in agreement with the data.

3.3 Scattering length

The K^-p scattering length obtained from our best fit compares closely with the value from Ref. [21] . These real part, however, have the opposite sign compared to those extracted from the *1s* K^-p atomic level shift data [17], that we did not try to fit. The existing data on the *1s* atomic level shift suffer from lack of accuracy and even the values within quoted error bars seem questionable [26]. Nevertheless, from

Table 4: K^-p scattering length

Authors [Ref]	a_{K^-p} (fm)	*1s* atomic level shift
Present work	− 0.63 + 0.76 i	*not fitted*
Martin [22]	− 0.66 + 0.64 i	*not fitted*
Tanaka & Suzuki [9]	− 1.11 + 0.70 i	*not fitted*
Tanaka & Suzuki [9]	+ 0.34 + 0.77 i	*fitted*

these data it is generally infered that the scattering length has positive sign. In trying to shed a light on this quest, we used the A_m obtained from the potential of Ref. [9] which fit all the hadronic low energy data and has the same sign for the scattering length as the atomic level shift data. We were able to reproduce their results using their non-relativistic potentials. From Table I we see that A_1 and A_3 do not differ too much from those obtained by our "SU(3) guided" potential. However, A_5 is much different in magnitude and its real part has the opposite sign. This desirable feature in reproducing the radiative capture branching ratios, is perhaps at the origin of the negative sign obtained for the scattering length.

4 Concluding remarks

We presented a coupled-channel formalism and reported the results of a comprehensive analysis of all the low energy K^-p data, except the *1s* atomic level shift. Results presented in this paper, reproduce well enough the existing strong and electromagnetic data from threshold up to $P_K^{lab} \approx 200$ MeV/c, with the relevant coupling constants close to their expected SU(3)-symmetry values. In all of the fits, the $\Lambda(1405)$ is produced as a bound $\bar{K} - N(\Sigma\pi)$ resonance, and the initial state interactions are very important for the radiative capture branching ratios. Our predictions underline clearly the need for more experimental investigations, specially for the in flight branching ratios. One of the main motivations is of course clarifying the nature of the $\Lambda(1405)$ resonance. Another crucial quest concerns the scattering length. Our results tend to show that reproducing *simultaneously* the measured electromagnetic branching ratios and the scattering length can not be achieved with the present approches. New and accurate measurements of the kaonic atoms level shifts are hence highly desirable.

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